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Restricted locality of quark-hadron duality in exclusive meson photoproduction reactions above the resonance region

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We show how deviations from the dimensional scaling laws for exclusive processes may be related to a breakdown in the locality of quark-hadron duality, i.e. the "restricted locality". For exclusive reactions like meson photo- and electroproduction above the resonance region, we explore the effects arising from such a local duality breaking and propose that it can be a possible source for oscillations about the smooth quark counting rule predicted by pQCD in the 90-degree differential cross sections.

Keywords: Quark-hadron duality; baryon resonances; meson photoproduction.

In recent years, the high-precision measurement of the nucleon structure functions [1] at the nucleon resonance region with high Q^2 gives access to a direct test of the Bloom-Gilman duality [2], which empirically connects the low-energy resonance phenomena with the high-energy scaling behavior. Namely, the electroproduction of N^* resonances at low energies and momentum transfers averages smoothly around the scaling curve of the nucleon structure function $F_2(W^2, Q^2)$ which is measured at large momentum transfers. Such a senario reflects the dual charactor of the strong interaction at the quark and hadron level, and also makes the interplay between the pQCD region and the conventional resonance region extremely interesting since special manifestation of the QCD dual charactor may show up due to the interference between the low-energy and high-energy processes [3]. In particular, it may provide novel insights into the observed deviations [4,5] from the pQCD predictions in exclusive meson photoproduction reactions above the nucleon resonance region, e.g. the energy dependence of data at $\theta_{c.m.} = 90^\circ$ which oscillates around the value predicted by the pQCD quark-counting rules [6].

The essential realization of duality was summarized by Close and Isgur [7] as "How does the square of sum becomes the sum of squares?". To show this, the

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model of two-body spinless constituents [8,7,9] serves as the simplest example. The general form for the transition amplitude for $\gamma(\mathbf{k})\Psi_0 \to \Psi_N \to \Psi_0\gamma(\mathbf{q})$ can be expressed as

$$
\begin{aligned}
M &= \sum_N \langle \Psi_0(\mathbf{P}_f, \mathbf{r})|[e_1 e^{-\frac{i\mathbf{q}\cdot\mathbf{r}}{2}} + e_2 e^{\frac{i\mathbf{q}\cdot\mathbf{r}}{2}}]|\Psi_N\rangle\langle\Psi_N|[e_1 e^{\frac{i\mathbf{k}\cdot\mathbf{r}}{2}} + e_2 e^{-\frac{i\mathbf{k}\cdot\mathbf{r}}{2}}]|\Psi_0(\mathbf{P}_i, \mathbf{r})\rangle \\
&= \sum_{N=0}^{\infty} \sum_{L=0(1)}^{N} [(e_1^2 + e_2^2) d_{00}^L(\theta) + 2e_1 e_2 d_{00}^L(\pi - \theta)] C_{NL} \mathcal{F}_{0N}^{(L)}(\mathbf{q}) \mathcal{F}_{N0}^{(L)}(\mathbf{k}) \ , \qquad (1)
\end{aligned}
$$

where Ψ_N is the harmonic oscillator wave function with the main quantum number N, and the imaginary part of Compton scattering as a sum over the intermediate resonances thus gives access to the structure function of "nucleon" Ψ_0. $\mathcal{F}_{N0}^{(L)}(\mathbf{k})$ denotes the transition from the initial to the intermediate state, and $\mathcal{F}_{0N}^{(L)}(\mathbf{q})$ for the intermediate decay to the final ground state.

At this stage, it is not important to consider details of the L-dependent factor C_{NL}. First note that in this simple model all terms of $L = odd$ for a given N are proportional to $\cos\theta$, and hence vanish at $\theta = 90^\circ$; thus we need consider only the parity-even states at $\theta = 90^\circ$, i.e. $N = 0,\ 2,\ 4\ ...$ with $L = N,\ N-2,\ \cdots\ 0$ for a given even N. The scattering amplitude at 90° can then be expressed as

$$
\begin{aligned}
M_{\theta=90^\circ} = e_0^2 \Bigg[& C_{00}\left(\frac{kq}{2\beta^2}\right)^0 + \frac{1}{2!}\frac{1}{3}(-C_{22} + C_{20})\left(\frac{kq}{2\beta^2}\right)^2 \\
&+ \frac{1}{4!}\frac{1}{35}(3C_{44} - 10C_{42} + 7C_{40})\left(\frac{kq}{2\beta^2}\right)^4 + \cdots \Bigg] e^{-(\mathbf{k}^2+\mathbf{q}^2)/4\beta^2} \ , \qquad (2)
\end{aligned}
$$

where $e_0 = e_1 + e_2$ is the total charge of "nucleon" Ψ_0.

Several points thus can be learned:

i) At the state-degeneracy limit of high energies, all the terms with $N \neq 0$ and $L = 0, \cdots, N$ in Eq. (2) would vanish due to the destructive cancellation. Only the C_{00} term survives:

$$
M = e_0^2 C_{00} e^{-\frac{(\mathbf{k}-\mathbf{q})^2}{4\beta^2}}\Big|_{\theta=90^\circ} = e_0^2 C_{00} R(t)\Big|_{\theta=90^\circ} \ , \qquad (3)
$$

where $R(t)$ is recognised as the elastic form factor for the Compton scattering [9] or more generally the quark-counting-rule-predicted scaling factor [6]. So we see that the smooth behaviour driven by the elastic form factor, which is the essence of the counting rules, effectively arises from the s-channel sum combined with the destructive interferences among resonances.

ii) Concerning the L-degeneracy breaking effect for any given N, each term of (N, L) corresponds to the excitation of an intermediate state with given N and L. The factor C_{NL}, which is essentially related to the mass position of each state, should be different for the individual states. This leads to oscillations around the simple result of Eq. (3), due to different partial waves not cancelling locally. We shall refer to this as "restricted locality".

Certainly, the simple model can only illustrate such a deviation in a pedagogic way. However, a similar phenomenon may have existed in physical processes due to the restricted locality of duality above the prominent resonance region. Notice that deviations from quark counting rules exist in certain exclusive reactions [4,5], e.g. the 90° differential cross sections of $\gamma p \to \pi^+ n$ at $W \sim 3$ GeV exhibit oscillations around the scaling curves predicted by the counting rules. We will show how the restricted locality of duality is naturally a source of such oscillations.

To generalize the above to the physical exclusive processes, we adopt effective Lagrangians for the constituent-quark-meson and quark-photon couplings, which were proposed by Manohar and Georgi [10] and extended to pseudoscalar meson photoproduction in Refs. [11,12]. Briefly, such a treatment highlights the quark correlations in the exclusive processes (including the Compton scattering). We can thus arrive at a general expression for the transition amplitudes for the s- and u-channels, i.e. the direct and the virtual resonance excitations:

$$M_{fi}^{s+u} = e^{-\frac{\mathbf{k}^2+\mathbf{q}^2}{6\alpha^2}} \left\{ \sum_{n=0}^{\infty} (\mathcal{O}_d^{cc} + (-\frac{1}{2})^n \mathcal{O}_c^{cc}) \frac{1}{n!} \left(\frac{\mathbf{k}\cdot\mathbf{q}}{3\alpha^2} \right)^n + \sum_{n=1}^{\infty} (\mathcal{O}_d^{ci} + (-\frac{1}{2})^n \mathcal{O}_c^{ci}) \right.$$
$$\left. \times \frac{1}{(n-1)!} \left(\frac{\mathbf{k}\cdot\mathbf{q}}{3\alpha^2} \right)^{n-1} + \sum_{n=2}^{\infty} (\mathcal{O}_d^{ii} + (-\frac{1}{2})^n \mathcal{O}_c^{ii}) \frac{1}{(n-2)!} \left(\frac{\mathbf{k}\cdot\mathbf{q}}{3\alpha^2} \right)^{n-2} \right\} , \quad (4)$$

where the multiplets are degenerate in n. The spin structures, charge and isospin operators have been subsumed in the symbol $\mathcal{O}$. Terms proportional to $(\mathbf{k}\cdot\mathbf{q}/3\alpha^2)^n$ denote correlations of c.m. - c.m. motions (superscript cc), while $(\mathbf{k}\cdot\mathbf{q}/3\alpha^2)^{n-1}$ and $(\mathbf{k}\cdot\mathbf{q}/3\alpha^2)^{n-2}$ denote the c.m. - internal (ci) or internal - internal correlations (ii), respectively. The subscript "d" ("c") denotes the direct (coherent) process that the photon and meson couple to the same (different) quarks in the transition. The coherent process is suppressed by a factor of $(-1/2)^n$ in comparison with the direct one for higher excited states. Note that the conventional Born terms will contribute to different parts: the nucleon pole terms included in the s- and u-channel, and the possible contact term and t-channel charged meson exchange included as part of the background terms due to gauge invariance. In the low energy regime, the degeneracy in n must break. In the SU(6)⊗O(3) symmetry limit, for a given n (≤ 2), multiplets of L- and S-dependent resonances can be separated in this model. In Ref. [12], the calculations were in agreement with experimental data up to $E_\gamma \approx 500$ MeV.

The dominant term comes from the correlation of the c.m.- c.m. motions at the two vertices ($n = 0, 1, \cdots$), while terms involving the c.m.- internal, or internal - internal motion correlation will be suppressed. For example, for $n = 0$ only the terms involving the c.m. - c.m. correlation contribute. These correlations are essentially the demonstration of the internal degrees of freedom of the nucleon system.

In the high energy limit where the degeneracy achieves, the leading term can be expressed compactly as:

$$M_{fi}^{s+u} = (\mathcal{O}_d^{cc} + \mathcal{O}_c^{cc} e^{-\mathbf{k}\cdot\mathbf{q}/2\alpha^2}) e^{-(\mathbf{k}-\mathbf{q})^2/6\alpha^2} \to (\mathcal{O}_d^{cc} + \mathcal{O}_c^{cc}) e^{-(\mathbf{k}-\mathbf{q})^2/6\alpha^2} \Big|_{\theta=90^\circ} , \quad (5)$$

where similar to Refs. [8,7,9] the scaling behavior can be realized at small $|t|$ due to the suppression of $e^{-\mathbf{k}\cdot\mathbf{q}/2\alpha^2}$ on the coherent term. At $\theta = 90°$, both direct and coherent process contribute and operators $\mathcal{O}_d^{cc}$ and $\mathcal{O}_c^{cc}$ now are independent of n. We conjecture that a similar factorization for the exclusive process may be more general than this nonrelativistic pictures, as suggested by the pedagogic model [9]. The form of Eq. (5) then represents the realization of duality, in particular, the emergence of the empirical quark counting rules after the sum over degenerate resonances at high energies. The exponent factor $e^{-(\mathbf{k}-\mathbf{q})^2/6\alpha^2}$ is thus regarded as the "typical" scaling law factor. Numerical results can be found in Ref. [13].

To summarize: we have discussed the relation between resonance phenomena and the dimensional scaling laws based on the quark-hadron duality picture at $2 \lesssim \sqrt{s} \lesssim 3.5$ GeV. In contrast to previous models for the deviations from quark counting rules, here we proposed that non-perturbative resonance excitations are an important source for such deviations. At specific kinematics, e.g. $\theta = 90°$, the oscillatory deviations could be dominantly produced by resonance excitations with "restricted locality", and this argument is general for photon induced two-body reactions on the nucleon. Although the formulation is nonrelativistic, we find it has been valuable to gain insights into the regime between the traditional resonance and partonic regions. We also suggest a non-trivial Q^2 dependence for such oscillations.

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References

1. I. Niculescu et al., Phys. Rev. Letts. **85**, 1182 & 1186 (2000).
2. E.D. Bloom and F.J. Gilman, Phys. Rev. D **4**, 2901 (1971).
3. G.P. Lepage and S.J. Brodsky, Phys. Rev. D **22**, 2157 (1980); *ibid.* **24**, 2848 (1981); N. Isgur and C. Llewellyn Smith, Phys. Rev. Lett. **52**, 1080 (1984).
4. "Photoproduction of Elementary Particles", edited by H, Genzel, P. Joos, and W. Pfeil, p16-268 (1973); R. L. Anderson *et al.*, Phys. Rev. D**14**, 679 (1976).
5. H. Gao, Plenary talk at EMI2001, Osaka, p115 (2001); L.Y. Zhu *et al.*, Phys. Rev. Lett. **91**, 022003 (2003); H. Gao and L.Y. Zhu, nucl-ex/0411014.
6. S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973); Phys. Rev. D **11**, 1309 (1975); V. A. Matveev *et al.*, Lett. Nuovo Cim. **7**, 719 (1973).
7. F.E. Close and N. Isgur, Phys. Lett. **B 509**, 81 (2001).
8. N. Isgur, S. Jeschonnek, W. Melnitchouk, and J.W. Van Orden, Phys. Rev. D **64**, 054005 (2001); W. Melnitchouk, Phys. Rev. Lett. **86**, 35 (2001); S. Jeschonnek and J.W. Van Orden, Phys. Rev. D **65**, 094038 (2002).
9. F.E. Close and Q. Zhao, Phys. Rev. D **66**, 054001 (2002).
10. A. Manohar and H. Georgi, Nucl. Phys. B **234**, 189 (1984).
11. Z. P. Li, Phys. Rev. D **50**, 5639 (1994); Z.-P. Li *et al.*, Phys. Rev. C **56**, 1099 (1997).
12. Q. Zhao, J.S. Al-Khalili, Z.-P. Li, and R.L. Workman, Phys. Rev. C **65**, 065204 (2002).
13. Q. Zhao and F.E. Close, Phys. Rev. Lett. **91**, 022004 (2003); work in preparation.